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Effect of additional herbage areas on grazing dairy cows in commercial farms: A GPS and LoRaWAN based case study on herbage intake and milk yield

A. Tom Chamberlain[1] Andrew Mead[2]
M. Jordana Rivero[3] J. Michael Wilkinson[4]
Rothamsted Research Ltd, West Common, Harpenden, Herts AL5 2JQ, United Kingdom

Abstract: Although grazing systems are widely used for lactating dairy cattle, feed intake is generally lower than in a fully housed system even when the feed quality and animals' nutritional requirements are similar. Running trials in commercial settings, long range wide area network (LoRa) technology and GPS positioning were used to track animal activity and position to investigate whether allocating additional herbage at a time linked to the cow's behaviour could increase productivity. In particular, we examined whether additional herbage allowance increases daily herbage intake and milk production without compro-mising grazing efficiency. Fourteen trials were undertaken on eight commercial dairy herds in 2019, 2020 and 2021 generally with cows in mid to late lactation. The 'GrazeMore' addi-tional grazing was compared to a standard daily herbage allocation. The 'GrazeMore' treatment period always followed an initial control period, sometimes with a subsequent control period. The composition of the grazing groups was largely consistent over the dura-tion of each trial, enabling the responses to be compared directly. Cow location could be tracked while they grazed and their grazing activity determined allowing the timing of addi-tional grazing allocation to be linked to grazing behaviour. Responses to additional 'GrazeMore' pasture allocations were inconsistent. The pattern of grazing was changed, but increased intakes during day grazing periods were sometimes balanced by reduced intakes in the following night periods, suggesting that factors other than the quantity of herbage on offer and the timing of its allocation during day grazing were responsible for limiting total 24 h herbage intake and milk production. Synchronising additional pasture allocation with grazing behaviour does not always increase herbage intake and milk production. We have also highlighted some of the challenges encountered while conducting research in com-mercial settings, as opposed to controlled experiments in research facilities.

Keywords: grazing management; Long range wide area network; grazing efficiency; grazing behaviour; Global Positioning System.

Efecto de áreas de pasto adicionales en el pastoreo de vacas lecheras en granjas comerciales: Un estudio de caso basado en GPS y LoRaWAN sobre el consumo de forraje y la producción de leche

Resumen: Aunque los sistemas de pastoreo se utilizan ampliamente para el ganado lechero lactante, el consumo de alimento es generalmente menor que en un sistema completamente estabulado, incluso cuando la calidad del alimento y los requisitos nutricionales del animal son similares. Se utilizaron pruebas en entornos comerciales, tecnología de red de área amplia (LoRa) de largo alcance y posicionamiento GPS para rastrear la actividad y la posición de los animales e investigar si la asignación de forraje adicional en un momento relacionado con el comportamiento de la vaca podría aumentar la productividad. En particular, examinamos si la asignación adicional de forraje aumenta el consumo diario de forraje y la producción de leche sin comprometer la eficiencia del pastoreo. Se realizaron catorce ensayos en ocho rebaños lecheros comerciales en 2019, 2020 y 2021, generalmente con vacas en lactancia media o tardía. El pastoreo adicional 'GrazeMore' se comparó con una asignación diaria estándar de forraje. El período de tratamiento con 'GrazeMore' siempre siguió a un período de control inicial, a veces con un período de control posterior. La composición de los grupos de pastoreo fue en gran medida consistente durante la

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[1]Chalcombe Ltd, Mountwood House, Biddenfield Lane, Shedfield, Southampton, Hants, SO32 2HP, United Kingdom.
[2]Rothamsted Research Ltd, West Common, Harpenden, Herts AL5 2JQ, United Kingdom.
[3]Correspondence author: M. Jordana Rivero jordana.rivero-viera@rothamsted.ac.uk Net Zero & Resilient Farming, Rothamsted Research Ltd, North Wyke, Okehampton, Devon, EX20 2SB, United Kingdom.
[4]University of Nottingham, School of Biosciences, Sutton Bonington Campus, Loughborough, Leics, LE12 5RD, United Kingdom.

duración de cada prueba, lo que permitió comparar las respuestas directamente. Se podría rastrear la ubicación de las vacas mientras pastaban y determinar su actividad de pastoreo, lo que permitiría vincular el momento de la asignación de pasto adicional al comportamiento de pastoreo. Las respuestas a las asignaciones adicionales de pastos de 'GrazeMore' fueron inconsistentes. Se cambió el patrón de pastoreo, pero el aumento del consumo durante los períodos de pastoreo diurno a veces se vio compensado por un consumo reducido en los períodos nocturnos siguientes, lo que sugiere que factores distintos de la cantidad de forraje ofrecido y el momento de su distribución durante el pastoreo diurno fueron los responsables de limitar el total de pastos. Consumo de forraje 24 h y producción de leche. Sincronizar la asignación de pastos adicionales con el comportamiento de pastoreo no siempre aumenta el consumo de forraje y la producción de leche. También hemos destacado algunos de los desafíos encontrados al realizar investigaciones en entornos comerciales, a diferencia de los experimentos controlados en instalaciones de investigación.

Palabras clave: manejo del pastoreo; Red de área amplia de largo alcance; eficiencia del pastoreo; comportamiento de pastoreo; Sistema de Posicionamiento Global.

Efeito de áreas adicionais de forragem em vacas leiteiras pastando em fazendas comerciais: Um estudo de caso baseado em GPS e LoRaWAN sobre consumo de forragem e produção de leite

Resumo: Embora os sistemas de pastoreio sejam amplamente utilizados para bovinos leiteiros em lactação, o consumo de ração é geralmente menor do que em um sistema totalmente alojado, mesmo quando a qualidade da ração e as exigências nutricionais do animal são semelhantes. A realização de testes em ambientes comerciais, a tecnologia de rede de longa distância (LoRa) e o posicionamento GPS foram usados para rastrear a atividade e a posição dos animais para investigar se a alocação de forragem adicional em um momento ligado ao comportamento da vaca poderia aumentar a produtividade. Em particular, examinamos se a oferta adicional de forragem aumenta a ingestão diária de forragem e a produção de leite sem comprometer a eficiência do pastoreio. Quatorze ensaios foram realizados em oito rebanhos leiteiros comerciais em 2019, 2020 e 2021, geralmente com vacas no meio ou no final da lactação. O pastoreio adicional 'GrazeMore' foi comparado com uma alocação diária padrão de forragem. O período de tratamento do 'GrazeMore' sempre seguiu um período de controle inicial, às vezes com um período de controle subsequente. A composição dos grupos de pastoreio foi bastante consistente ao longo de cada ensaio, permitindo que as respostas fossem comparadas diretamente. A localização das vacas poderia ser rastreada enquanto pastavam e a sua atividade de pastoreio determinada, permitindo que o momento da atribuição adicional de pasto fosse ligado ao comportamento de pastoreio. As respostas às alocações adicionais de pastagens 'GrazeMore' foram inconsistentes. O padrão de pastoreio foi alterado, mas o aumento do consumo durante os períodos de pasto diurno foi por vezes compensado por consumos reduzidos nos períodos noturnos seguintes, sugerindo que outros fatores para além da quantidade de forragem oferecida e o momento da sua distribuição durante o pastoreio diurno foram responsáveis por limitar o consumo total de forragem. Consumo de forragem em 24 h e produção de leite. Sincronizar a alocação adicional de pastagens com o comportamento de pastoreio nem sempre aumenta o consumo de forragem e a produção de leite. Também destacamos alguns dos desafios encontrados durante a realização de investigação em ambientes comerciais, em oposição a experiências controladas em instalações de investigação.

Palavras-chave: manejo de pastagem; Rede de longa distância; eficiência de pastoreio; comportamento de pastoreio; Sistema de Posicionamento Global.

Introduction

Global competition for limited arable land that can produce either human food or animal feed highlights a key role for grazed livestock in producing human food from less productive pastureland that cannot be cultivated to produce crops (Wilkinson and Lee, 2018). Prediction and management of herbage growth, allocation of herbage to grazed livestock and optimising production per animal and per hectare are critical challenges facing pas-ture-based farmers (Wilkinson *et al*., 2020). A major objective in pasture management is to provide an adequate daily supply of dense herbage comprising young vegetative growth throughout the grazing season to meet the nutritional requirement of the grazing animal (McGilloway *et al*., 1996). This must be achieved despite potentially large variations in the rate of plant growth due to season, temperature, water and nutrient supply. In addition, the feed intake of the dairy cow varies with live weight, milk yield and stage of lactation (Chamberlain and Wilkinson, 1996). The diurnal grazing pattern emerges from a series of grazing decisions such as 'when' to begin, the intensity (i.e., herbage intake rate), 'what' frequency and 'how' to distribute the grazing events in time (Gregorini, 2012) and, for a milking cow, what other activities she has to perform such as visiting the milking parlour. Therefore, the causes for a grazing cow to initiate and terminate the grazing event are complex and multifactorial (Chilibroste *et al*., 2015).

Although grazing plays a central role in dairy cow nutrition in many regions of the world, low herbage intake by the grazing animal is a major limitation to herd productivity (Bargo *et al*., 2003). Target levels of daily herbage allowance in temperate intensive perenni-al-ryegrass-based dairy grazing systems (e.g., New Zealand, France) are 20 to 30 kg DM/head to support a daily intake of 15 to 17 kg DM/head (Wilkinson *et al*., 2020). In contrast, typical daily DM intake by dairy cows given total mixed rations is some 33 % higher than that of cows given grazed pasture (Wilkinson and Lee, 2018). Further, the intake response by grazed cows to increased daily herbage allowance is at the expense of efficiency of pasture utilisation (Baudracco *et al*., 2010). Previous research by MacDonald *et al*. (2001) in New Zealand examined farmlets with varying stocking rates and demonstrated that milk yields increase as stocking rate and grass supply rise. However, it was observed that grazing effi-ciency decreases as cows become more selective. Thus, a balance has to be struck between maximising herbage intake and maintaining an acceptable proportion of available herbage that is actually consumed by the animal. The area of pasture to be allocated to a herd of cattle for grazing varies according to size of herd, quantity of herbage available and planned grazing intensity (proportion of the sward to be removed). Having calculated the appropriate area of land to be allocated, traditionally animals are introduced to new pasture at a time convenient to the herd manager. In the case of rotationally grazed swards, this occurs after fences have been moved to allow access by livestock to a new area of ungrazed herbage. Timing of new pasture allocation to dairy cows normally occurs when the herd is withdrawn from the field to be milked. Consequently, allocation of new herbage may not be in syn-chrony with the natural pattern of grazing behaviour (Abrahamse *et al*., 2009; O'Driscoll *et al*., 2010).

Development of global positioning systems (GPS) (Turner *et al*., 2000; Rivero *et al*., 2021), sensors (accelerometers) capable of monitoring/measuring animal behaviour, and long-range wide area networks (LoRaWAN) (Miles *et al*., 2020) introduces the possibility of controlling grazing on commercial dairy farms. GPS data can be used to determine when the cows are in the grazing field and accelerometers fitted to the cow can model when the cow is grazing. Such data can be collected in real-time over the LoRa network and processed in the 'cloud' to determine when on-farm actions (such as gate opening) should be triggered with information relayed back through the LoRa network to in-field actuators.

Preliminary visual observations (ATC) of cows in commercial herds showed an intensive period of grazing at the start of the grazing bout followed by a period of rumination, confirmed by the findings reported by Sheahan *et al*., (2013). The cows then commenced a second grazing bout ranging over ground they had already grazed but with less intense grazing and more sward selection to avoid contaminants, e.g., dung pats. This behaviour of modifying the grazing (e.g., biting rate) due to the presence of contaminants has been previously re-ported by Bao *et al*., (1998) who concluded that selective grazing exists due to the presence of dung and is conditioned by dung distribution. Ad hoc trials in 2017 allocating fresh grazing at the start of the secondary bout led to the herd of cows rapidly moving to the new area followed by a bout of intensive grazing (Chamberlain and Kodam, 2019) . The objective of these trials was to determine if the starting time of the secondary grazing bout could be determined automatically, and a new grazing allocation opened up without any human intervention. Such automation would be needed for any commercial application.

The work reported here comprised a feasibility study to test two hypotheses under commercial farm settings: 1) Allocation of a new area of herbage to be grazed can be synchro-nised with natural grazing behaviour, determined by GPS and accelerometer data collated through LoRaWAN, and 2) Provision of additional herbage when a new grazing bout is imminent increases daily herbage intake and milk production in commercial dairy herds without compromising grazing efficiency. In addition, the suitability of LoRaWAN technology as a tool to collate data effectively was assessed. We have also highlighted some of the challenges encountered while conducting research in commercial settings, as opposed to controlled experiments in research facilities.

Materials and Methods

The ethical implications of the project were considered by ATC, who was a Named Veterinary Surgeon with the UK Home Office. Procedures that directly involved animals were the fitting and removal of neck collars. Commercially available weighted cow neck collars were used (Kerbl, UK) with a gross weight of 850 g, and these were considered indistinguishable from other commercial collars such as activity monitors. The procedures were therefore classed as 'non-regulated' under the Animals (Scientific Procedures) Act 1986 (ASPA), and further ethical consideration was not applicable.

Implementation of Grazing Trials

Fourteen trials were undertaken on eight commercial dairy units between April and September 2019, July-August 2020 and April-May 2021 in the counties of Dorset, Shropshire, Somerset, Wiltshire, located in the south of England (UK). The country is characterised by a temperate climate. The accumulated annual precipitation for the region where the trials were conducted is approximately 720 mm pa (evenly spread through the year), with an average minimum and maximum summer air temperature of 8 and 21 °C, respectively (Met_Office, 2023). Pastures are usually mixed swards comprising perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.).

Eight collaborating farmers (different dairy units, see Table 1) allowed temporary installation of a single LoRaWAN 'gateway' on their farm to enable grazing behaviour to be monitored remotely. Dairy units were initially selected by phone interview on the basis of their grazing infrastructure, i.e., rotational paddock grazing systems, good water supply and trough provision, temporary fencing within paddocks, little or no buffer feeding, regular plate meter readings and milk recording of individual cow's yield. Each unit operated separate 'day' and 'night' grazing allocations with twice-daily milking. Day fields were grazed between the end of morning milking and the start of evening milking and night fields were grazed between the end of evening milking, and the start of morning milking (Sheahan *et al*., 2013).

The 'Control' treatment consisted of the usual pasture allocation for the farm, herd and stage of the grazing season as determined by the farm management. To test hypothesis 2, an additional area of pasture for the 'GrazeMore' treatment was allocated daily during the day grazing period, at the start of the herd's second major grazing period (usually mid-morning), calculated as a percentage of the initially allocated amount; the percentage increase varied between trials (Table 1). The timing for the allocation of the new 'GrazeMore' area was not set at a fixed time of the day (see section 2.4.). Both treatments were applied to the same groups of animals at different times (e.g., 'Off-On': 'Control' then 'GrazeMore' or 'Off-On-Off': 'Control', then 'GrazeMore' and then 'Control' again; Table 1). In each trial, the initial area of pasture allocated for the day grazing period, which commenced after the morning milking, was determined based on existing farm practices including levels of pre-grazing herbage mass and expected residual covers.

As the trials were run on commercial dairy farms, group selection was initially conservative, where possible, to limit the impact of any milk yield depression on herd output. Where cows were grouped within the herd for management purposes, the 'Low' yielding group was generally selected. The milk yield, stage of lactation and supplemental feeding allocation at the start of each trial are shown in Table 2. Supplementary feeding was a pelleted compound feed offered twice a day in the milking parlour that was formulated to 16 % or 18 % crude protein in the fresh weight. The supplementary feed allocation was determined by the milking parlour software based on individual cow milk yields at the start of the trial and was held at a fixed amount throughout the trial. To avoid milk yields becoming too separated from supplementary feed allocations the trials were limited to 20 days and then the parlour software reset the feeding allocations.

Identification of Grazed Fields and Individual Animals

Selected farms were geo-mapped using a combination of Scribble Map software (52 Stairs Studio Inc. Ontario, Canada) and ground truthing with a handheld GPS device (iPhone 6 augmented with a Garmin Glo2 portable GPS/GLONASS sensor) to identify lati-tude/longitude coordinates of the apex points of individual fields.

Eight cows in each trial, selected from each herd (Table 1) as being representative in terms of age, stage of lactation and milk yield, were each fitted with weighted (500g) neck collars (Kerbl UK Limited, Oakham, UK), on which were mounted long-range (LoRa) nodes de-veloped in a previous project (InnovateUK project, 132355). The nodes weighed approxi-mately 350 g and contained a battery (Saft 33600, 3.6V, 17Ah, Saft Groupe SAS, Leval-lois-Perret, France) and a custom-built printed circuit board (Figure 1). The LoRa nodes recorded GPS position and accelerometer data.

Figure 1. Neck collar and 'node' box for GPS transmission.

Cow Behaviour and Milking Times

Using the node accelerometer data, cloud-based algorithms were developed to identify a change from the intensive grazing that is seen when cows enter a new grazing area to a ruminating behaviour (around 60 to 120 minutes post field entry). Cows will generally ru-minate for 30 to 90 minutes before starting to graze again (Figure 2). A logistic regression was fitted relating the accelerometer reading variability to observed animal eating behaviour throughout each 120 second interval to predict the probability that a cow was grazing (pGraze) as described by Chamberlain and Kodam (2019). GPS and pGraze data were (nominally) reported for each period of 120 seconds.

Individual cow position and behaviour data were combined to summarise herd-level activities. The GPS fix for each cow was related to the field apex database to determine in which field the cow was grazing. Once five of the eight cows were in a particular field it was concluded that the entire group had entered that field. Milking times were defined at the period when five out of eight cows were in the milking complex area. Similarly changes in grazing behaviour were examined at the individual level and once five out of eight cows had changed behaviour then it was concluded the group had changed behaviour. This removed issues with outliers due to particular animals being kept in the milking buildings for husbandry interventions or unusual behaviours such as fighting or oestrus. If monitoring halted for any of the eight animals, the decision threshold was modified accordingly, always ensuring that at least 60 % of the monitored animals had changed behaviour before decisions were made.

Table 1. Collaborating dairy units, dates of trials, dairy cows herd size, treatment allocation design and numbers of days in each treatment period.

Dairy Unit	Trial No.	Start date	End date	Grazing group size (type[1])	Annual milk yield (litres/cow)	Design[2]	Number of days[3]			Comments[4]
		2019					Control	GrazeMore	Control	
A	1	26 April	10 May	100 (lows)	9300	Off-On +20 %	127	-		Inadequate grazing availability
B	2	26 April	10 May	250 (whole herd)	10000	Off-On + 20 %	8	6	-	Inadequate grazing availability No individual cow milk yield data
C	3	20 May	7 June	150 (lows)	9000	Off-On +20 %	8	8	-	
D	4	20 May	7 June	200 (whole herd)	9000	Off-On + 20 %	134	-		Variable pasture quantity and quality. No individual cow milk yield data
E	5	17 June	5 July	190 (whole herd)	7000	Off-On +20 %	9	10	-	No individual cow milk yield data
A	6	17 June	5 July	100 (lows)	9300	Off-On +20 %	11	5	-	
C	7	22 July	3 August	150 (lows)	9000	Off-On +20%	n/a	n/a[4]	-	Inadequate grass due to drought

Table 1. Collaborating dairy units, dates of trials, dairy cows herd size, treatment allocation design and numbers of days in each treatment period. **(continuación)**

Dairy Unit	Trial No.	Start date	End date	Grazing group size (type[1])	Annual milk yield (litres/cow)	Design[2]	Number of days[3] Control	GrazeMore	Control	Comments[4]
		2019								
D	8	22 July	3 August	200 (whole herd)	9000	Off-On +20 %	n/a	n/a[4]	-	Inadequate grass due to drought
E	9	2 Sept	16 Sept	190 (whole herd)	7000	Off-On +20 %	9	6	-	No individual cow milk yield data
		2020								
F	10	6 July	25 July	90 (lows)	10200	Off-On +40 %	7	10	-	Limited grazing availability No individual cow milk yield data
G	11	3 August	23 August	190 (lows)	8900	Off-On +40 %	7	11	-	
		2021								
G	12	12 April	2 May	240 (lows)	8900	Off-On +30 %-Off	11	7	3	
G	13	12 April	2 May	145 (mids)	8900	Off-On +30 %-Off	12	6	4	
H	14	10 May	30 May	250 (whole herd)	8500	Off-On +30 %-Off	10	7	1	Intermittent grazing data capture due to terrain

[1] 'Lows' = cows in late lactation; 'mids' = cows in mid lactation.
[2] 'On' = additional day grazing allocated in 'GrazeMore' period as percentage of total day grazing allocation in 'Off" period
[3] 'Off'-'On' or 'Off'-'On'-'Off.

Table 2. Main performance and feeding characteristics of the cows selected in trials used for analysis of feed intakes or milk yields (from parlour software or commercial milk recording).

Trial No	Group	Stage[1]	Milk yield (l/day) in group at start of trial Median	IQR[12]	Days in milk at start of trial Median	IQR	Supplementary feed allocation (kg/day) at start of trial Median	IQR
3	150	lows	21.1	8.9	241	103	2.6	3.1
5	190	whole herd	14.6	6.5	283	35	2	0
6	100	lows	15.4	8.4	270	63	3.5	1
9	190	whole herd	22.1	10.2	18	15.5	6	0
11	190	lows	20.1	6.8	258	97	3.2	3.8
12	240	lows	23	7.5	228	79.5	2.3	3
13	145	mids	29	7.3	127	66	2.6	3.3
14	250	whole herd	29.1	10.8	150	136	5.6	4.3

[1]'lows' = cows in late lactation; 'mids' = cows in mid lactation.
[2]IQR: inter quartile range.

Movement of Fences and Daily Herbage Allocations

A recoil gate (Gallagher UK) and battery/solar-powered opening device (modified Batt Latch, Novel Ways Limited, Taupo, New Zealand) were fitted to sections of paddock fencing to facilitate opening and allow herd access to the additional grazing area each day during the 'GrazeMore' treatment period of each trial. The trigger of gate opening varied according to milking times and amounts of grazing allocated in the initial area but was constrained to be at least 90 minutes before the start of (planned) afternoon milking and was triggered by changes in the behaviour of the eight selected (monitored) cows (detailed information on grazing allocations is shown in Chamberlain *et al.*, (2022b)).

Sending outward-bound messages to the BattLatch gate opener was unreliable due to line-of-sight issues in many fields. As an alternative a solar-powered SMS-Modem enabled BattLatch was in-stalled in Trial 10, but the power draw required for regular checks for trigger messages necessitated frequent retrieval and battery recharging. In Trials 9 to 14, the gate opener

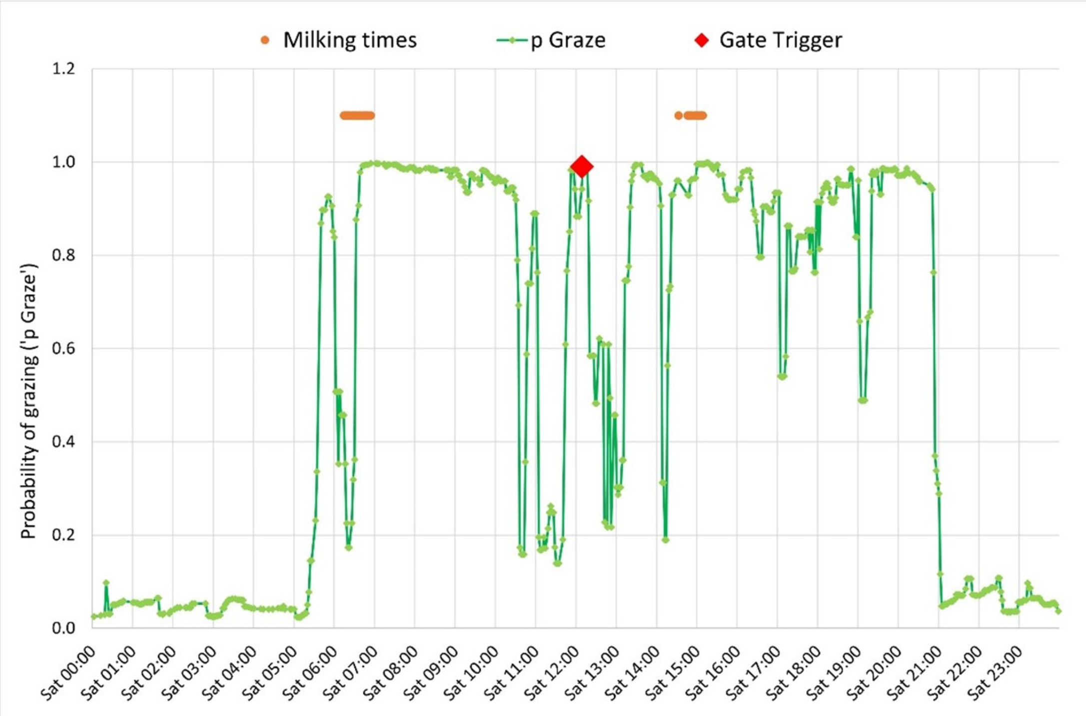

Figure 2. Typical plot of pGraze against time for one cow on one day in one trial (Cow 901, 8 Aug 2020, Trial 11) during the 'Control' treatment. pGraze shown as a rolling 10 min average to aid graphical clarity, timing of milking determined from cow location, timing of 'Gate Trigger' determined from activity analysis.

battery recharging. In Trials 9 to 14, the gate opener was programmed manually. Node data was downloaded daily at 8 pm, analysed and assessed that evening. The next day, the final setting of the gate trigger time was manually entered into the standard BattLatch firmware.

Field sizes were measured and grazing plot allocations were calculated using anticipated herbage intakes and grazing group sizes (determined from farm records). Grazing areas were defined with electric fencing, and herbage residuals were measured after each grazing for both day and night fields (see Supplementary Table 1 and 2 in Chamberlain *et al.*, 2022d).

Herbage Mass, Dry Matter Intake and Grazing Efficiency

Quantities of herbage DM mass per hectare were estimated with a rising plate meter (F200 model, Jenquip, Feilding, New Zealand) daily during each trial to provide estimates of both pre- and post-grazing for all allocated day and night grazing areas. At each measurement occasion, a total of 40 readings were taken at random across the paddock (excluding dung patches) and averaged. Duplicate sets of 40 readings were taken and if the average values of the two sets differed by more than 200 kg DM/ha a further replicate set of 40 readings was collected. Herbage DM intake per cow was estimated using the pre- and post-grazing herbage DM mass estimates, the area allocated for grazing, and the number of animals grazing each day (Lukuyu *et al.*, 2014). Grazing efficiency was calculated from herbage DM allowance per animal and DM consumed over each grazing period.

Milk Yield

Milk yield data were collected from herds that used GEA (GEA Group AG, Düsseldorf, Germany) recording equipment in milking parlours (herds A, C, G, H in Table 1). Data were collated from all the cows grazing in the groups (including the eight selected with GPS collars as shown in the Results section; detailed information can be found in Chamberlain *et al.*, 2022d). Software routines (Visual Basic, Microsoft 2016) were written to extract daily milk yield data from data feeds and converted to a standard format showing daily milk yields for each cow in the trial. Data were filtered as follows:

•Daily records were set to missing, but animals still retained for the other days where yields were > 200 % or < 50 % of the previous day's yield, accounting for double or missing recordings at one milking,

•Data associated with animals with an unknown age/ lactation were removed,

•Data for animals from recording more than 405 days after calving or less than 10 days post calving were removed, and

•Data for animals with missing milk yields on two or more consecutive days were removed.

Most of the trials were carried out on cows in mid to late lactation (Table 1) as the authors did not feel they could ask the participating farmers to expose their best, highest yielding cows to a novel trial procedure. As such, most animals would have been past peak yield and yields would be naturally falling. As the 'GrazeMore' treatment always followed the 'Control' period, this could have con-sistently reduced milk yields in the 'GrazeMore' period. To counter this effect, milk yields were corrected for stage of lactation as follows. Daily individual cow milk yields were determined for the 60-d period before each trial began (the GEA software system only holds individual milk yields each milking for 60 days). Primiparous and multiparous animals were then analysed separately. Milk yields through lactation were referenced to the milk yield at 150 days (around peak yield). To reduce the impact of random variation between days around 150 days, the average milk yield for each animal three days before and 3 days after 150 days was averaged to give a 7-day average for each parity group to determine the reference yield. Average yields for each parity group at other stages of the lactation were then expressed as proportions of the 150th day reference yield and these pro-portions were used multiplicatively to correct individual daily milk yields for all animals during the trial.

Experimental Design

To enable the assessment of hypothesis 1 trials were implemented using commercial dairy herds to ensure that the trial results were representative of potential impacts on other commercial dairy herds. Animals were exposed to each treatment for a number of days to enable the elimination of any carryover effects of the previous treatment. A 'cross-over' design approach using pairs of commercial dairy units in close geographical proximity and with similar characteristics (environ-ments, animals) was not possible as suitable pairs of farms could not be identified from the pool of available candidates. Instead, 'an 'Off-On-Off' treatment structure was selected: period of time (days) under the Control treatment, followed by a period of time (days) under the GrazeMore treatment, followed by a further period of time (days) under the Control treatment. However, available grazing resources and timescales for the early trials meant that this approach could not be implemented initially, so a simpler 'Off-On' treatment structure was implemented for most of the trials. In this structure, the group of animals first experienced the 'Control' treatment for a number of days, followed by same group experiencing the 'GrazeMore' treatment for a number of days.

Fourteen grazing trials were undertaken on eight commercial dairy units during the 2019, 2020 and 2021 grazing seasons (details of individual trials are shown in Table 1), with the aim of having equal length periods for the 'Control' and 'GrazeMore' treatments in each trial (including where the 'Control' treatment was applied in two periods at the start and end of each trial). In all trials a minimum period of 7 days was included for each treatment. Herds were allocated a fresh grazing paddock each morning and evening. The experimental unit was assumed to be the group of grazing animals allocated to the combination of a day grazing paddock and a night grazing pad-dock during a particular 24-hour period. Response variables associated with herbage intake could only be measured (estimated) for the whole group of animals (i.e., for the selected paddocks), whilst milk yields could be measured for each individual animal, and behavioural data for only the 8 (nominally) selected animals monitored using the nodes. Where data were collected for individual animals, animal was used as a blocking (random) term in any analyses, or data were summarised as mean values per animal prior to analysis (with the number of animals constant across all days of a particular trial), and treatment differences were still assessed relative to the identified experi-mental unit. Responses on the first day on which a treatment was applied were omitted from the analyses, as these responses might have been influenced by the previous treatment, particularly given the expected lag in milk yield productivity relative to grazing intake. The temporal ordering of the treatments ('Control' followed by 'GrazeMore') meant that some adjustment in milk yield productivity was needed to account for the usual changes in productivity with increasing "days in milk" (DIM). Herd lactation curves were obtained for each trial and observed yields multiplicatively adjusted for each animal separately to 150 DIM.

Statistical Analysis

Due to logistical constraints, different subsets of the trials were used to investigate different aspects of the treatment responses. For the analysis of the temporal dynamics of grazing activity, the highest quality data were regarded to come from the later trials (10, 11, 12, 14); when the analysis of these four trials failed to show a consistent increase in feed intakes if was considered that there was little to be gained from analysing further trials. Reliable individual daily milk yield data were only available on farms A, C, G and H and hence for 6 trials (3, 6, 11, 12, 13, 14). In some trials the availability of grazing or the management of the herd and grazing allocations were considered to have limited, and as such, reliable grazing intake data were only available for 8 trials (3, 5, 6, 9, 11, 12, 13, 14).

Data for pre-grazing herbage mass, post-grazing residual herbage mass, herbage intake and grazing efficiency were analysed for treatment differences in three different temporal periods:

• Day grazing period – directly assessing the impact of providing the additional grazing area in the 'GrazeMore' treatment.

• Night grazing period – to assess possible compensatory changes in herbage intake.

• 24-hour grazing period – combined data, considered likely to influence energy intake, and hence milk yield.

Differences in these grazing intake responses between the two treatments ('Control' *vs.* 'GrazeMore') were assessed for each trial separately using two-sided, two-sample t-tests, preceded by F-tests to assess the assumption of equal variance (i.e., equal day-to-day variation within each treatment period). Where the F-test provided no evidence (at the 5 % significance level) for differ-ences in variances between the treatments, a standard t-test was applied. Where the F-test pro-vided evidence for differences in the variances, an alternative Welch test was applied. Results of these tests are presented in terms of the difference between the treatments, a standard error of the difference (SED) for this comparison, the t-statistic (t-stat), the number of degrees of freedom (df) and a p-value (t-prob). Tests with non-integer degrees of freedom indicate where the alternative Welch test was applied.

Node efficiency in terms of data transmission and cloud capture was assessed for Trials 10, 11, 12 and 14 where cows were grazed day and night with no buffer feeding. Efficiency was calculated as a percentage of the maximal number of data packets that could have been received in each 24-hour period. In practice, the number of data records was usually much lower than the nominal 30 per hour, and records were not all reported at the same time points in each hour for each animal, such that the data needed filtering to provide a reliable assessment over a longer period (e.g., an hour) of the mean probability of grazing in that period.

Grazing data from node transmission were analysed for Trials 10, 11, 12 and 14. For each trial data are pGraze values which were reported, nominally, every 2 minutes through the duration of the trial. Linear interpolation was applied to fill gaps between reporting points and provide a regular se-quence of 30 pGraze estimates per hour. Interpolated datasets were obtained for each of the monitored animals in each trial and mean values per hour calculated from the 30 interpolated values for each hour. If there were 10 or fewer reporting points in an hour or where the maximum gap between reporting points was more than 20 minutes the hourly mean was set to missing (and hence the data excluded from the analysis).

The analysis of these data allowed for differences between animals (nodes) and between days, assessing for differences between the treatments (assigned to the different days of the trials), between hours (times of day – expected to be the dominant source of variability in the data), and the interaction between treatment and hour, using analysis of variance (ANOVA), again, with separate analyses for each of the trials. Interest was in whether there were overall differences in the probability of grazing (i.e., pGraze; Chamberlain and Kodam (2019)) between the two treatments, and whether the distributions of grazing probabilities over a day were affected by the treatments. To cope with the anticipated variance heterogeneity of the bounded probability values, the data were logit transformed prior to analysis. All analyses were implemented in Genstat 21st Edition (VSN International, 2021).

Results

Grazing Patterns Through 24h Periods

Issues with node efficiency (see section 3.5) meant that there were parts of some of these trials where pGraze data were not recorded frequently enough to allow interpolated datasets to be produced, impacting on the reliability of treatment comparisons. A summary of pGraze data for Trials 10, 11, 12 and 14 is presented in Table 3, with differences in within-day grazing patterns shown through plots of the back-transformed means in Figure 3. Red diamonds in Figure 3 identify hours when the treatment difference was significantly different from zero. Yellow bars show av-erage milking periods over the trial period, and the red star indicates the average time when access to the 'GrazeMore' additional grazing was provided.

For Trials 10 and 12, where full days of reporting points were missing in the middle of the trials, the proportion of missing hourly means included these periods (67 consecutive missing hours for each node in Trial 10, amounting to 17.4 % of the total number of hourly means; 65 or 66 consecutive missing hours for each node in Trial 12, amounting to 15.2 % of the total number of hourly means), primarily impacting the 'GrazeMore' treatment summaries. For Trial 14, records were unavailable for the last 6 days of the trial (data omitted for 3 days due to low frequencies of observations), including much of the 'GrazeMore' treatment period, so the comparison of the treatments was based on only two reliable days for that treatment. It is also important to note the much higher percentage of missing hourly means for this trial and the much higher level of background variability, reflecting less consistency both between animals within a day and between days for each animal. For Trial 11, the missing data were for several hours at the start of the 'Control' treatment period.

Table 3. Grazing activity based on node transmission (Trials 10-12, 14) of dairy cows submitted to two herbage allocation methods ('GrazeMore' and 'Control') in commercial farms. Separate anal-yses (ANOVA) were applied to the data for each trial.

Trial	10	11	12	14
Days – Control	6	7 [1][1]	10	9
Days – GrazeMore	10 [2][1]	11	8 [2][1]	5 [3][1]
Nodes (animals)	7	8	7	8
No. of hourly means	2688	3264	3024	2112
Percentage hours missing	22.4	13.6	18.3	48.1
Treatment effect: F-test	0.63	0.09	2.40	0.87
df[3]	1, 12	1, 15	1, 14	1, 9
p-value	0.444	0.766	0.143	0.375
Control mean pGraze	0.420 (-0.323)2	0.367 (-0.547)	0.345 (-0.639)	0.343 (-0.652)
Grazemore mean pGraze	0.403 (-0.391)	0.379 (-0.496)	0.328 (-0.718)	0.409 (-0.369)

[1] Number of missing days for all animals. [2] Logit transformed data shown in parentheses. [3]df = degrees of freedom. [4] SED = standard error of the difference. [5]LSD = least significant difference.

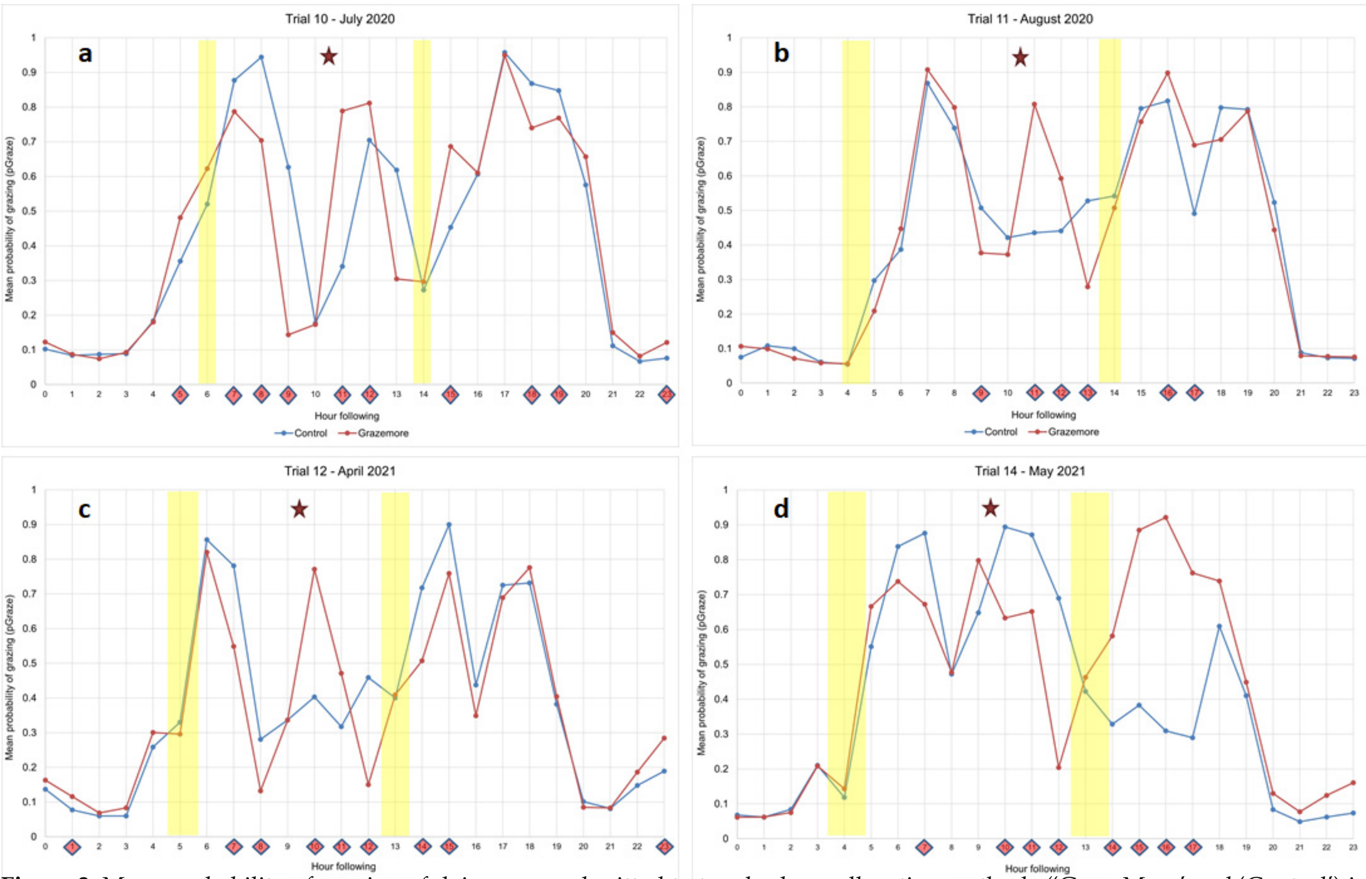

Figure 3. Mean probability of grazing of dairy cows submitted to two herbage allocation methods ('GrazeMore' and 'Control') in commercial farms; a) Trial 10, b) Trial 11, c) Trial 12, and d) Trial 14. Red diamonds indicate hours where there were significant ($p < 0.05$) differences between the 'Control' and 'GrazeMore' treatment means, yellow bars indicate the average milking periods, and red star indicates the average time when the gate to additional grazing was opened for the 'GrazeMore' treatment.

Despite the numerical differences in the overall mean proportion of time grazing (trials 11 and 14 in favour of 'GrazeMore', and trials 10 and 12 in favour of 'Control'), for none of the trials were the differences significantly different from zero. The largest difference was seen in Trial 14, but the greater background variability stopped this difference being significant, though the same difference would have been statistically significant in the other trials. Overall mean pGraze values can be used to estimate the total time grazing per day, so, for example, for Trial 10 the estimated total daily grazing time for the 'Control' treatment was 10.08 hours (10 hours and 5 minutes), reducing to 9.67 hours (9 hours and 40 minutes) for the 'GrazeMore' treatment.

In all four trials there was a highly significant effect of the hour, as was expected given the usual pattern of grazing, and a highly significant, though smaller, interaction effect. These interaction effects are best interpreted by identifying hours where the 'GrazeMore' treatment either signifi-cantly increased or decreased the probability of grazing compared with the 'Control' treatment. Two of the trials (11, 12) showed a significantly higher mean pGraze for the 'GrazeMore' treatment for a couple of hours immediately after the access to the additional pasture, but a significantly lower mean pGraze for the 'GrazeMore' treatment in the immediately following hour. There were further, smaller treatment differences, often with the 'Control' treatment mean pGraze being significantly higher, at other times of day. For Trial 10, there was more of a shift in the timing with the 'GrazeMore' treatment bringing grazing bouts earlier. In Trial 14, a rather different pattern was seen, with the 'GrazeMore' treatment having significantly lower mean pGraze values in the period immediately after the access to additional grazing, and significantly higher mean pGraze values in the sub-sequent 4 or 5 hours (after the evening milking). However, the 'GrazeMore' treatment data were less reliable for this trial, based only on the first two days after the change of treatments.

Herbage Mass Pre-Grazing (Cover) and Post-Grazing (Residual)

Herbage mass pre-grazing ranged from 2000 to 4500 kg DM/hectare (see Supplementary Table 1 in Chamberlain *et al*., 2022d), with most values within the target of 3000 to 4000 kg DM/hectare recommended to be offered to dairy cows grazing temperate grasslands (Wilkinson *et al*., 2020). Significant differences in quantities of herbage mass pre-grazing were recorded between 'Control' and 'GrazeMore' treatments in some trials, but differences between trials were inconsistent (see Supplementary Table 1 in Chamberlain *et al*., 2022d). Mean 24 h herbage mass pre-grazing was significantly higher for 'GrazeMore' than 'Control' in Trials 5, 12 and 14 ($p < 0.05$) and tended to be higher ($p < 0.10$) in Trial 11 and lower in Trials 9 and 13. Levels of post-grazing residual herbage mass ranged from 1500 to 3000 kg DM/hectare, with most values close to 2000 kg DM/hectare (see Supplementary Table 2 in Chamberlain *et al*., 2022d). Mean 24 h residual herbage levels were significantly higher for 'GrazeMore' than 'Control' in Trials 12 and 14 ($p < 0.05$).

Herbage Intake and Grazing Efficiency

Average daily herbage intake and grazing efficiency (expressed as intake as a % of kg DM al-lowance per cow per day) are shown in Table 4. Offering additional herbage in the 'GrazeMore' treatment periods had inconsistent effects on herbage intake. Total 24 h intakes were significantly higher for 'GrazeMore' than 'Control' in Trials 5 ($p = 0.022$), 6 ($p = 0.001$), 12 ($p = 0.020$) and 14 ($p = 0.002$), significantly lower in Trial 3 ($p = 0.044$) and similar in Trials 9, 11, and 13. In Trials 9 and 13, increased intakes during the day (when additional herbage was offered in 'GrazeMore' periods) were balanced by reduced intakes in subsequent night periods. In Trial 11, intakes were similar in both day and night periods (Table 4).

The largest increases in 24 h herbage intake for the 'GrazeMore' treatment were 3.9 kg DM/cow in Trial 5, 3.1 kg DM/cow in Trial 12 and 6.3 kg DM/cow in Trial 14. In these trials, increased intakes during the day were not balanced by reduced intakes at night, as seen in Trials 9 and 13. Overall, daily herbage intake averaged 13.8 kg DM/cow for the 'Control' treatment and 15.1 kg DM/cow for the 'GrazeMore' treatment.

There were no consistent effects of treatment on grazing efficiency (Table 4). The lower grazing efficiency recorded in 'GrazeMore' periods in Trials 3, 9, 11, and 13 reflected the greater amount of herbage DM allowance per cow during day periods which were not reflected in higher levels of herbage intake.

Milk Yield

Average daily milk yields, corrected for the stage of lactation to 150 days in milk for individual animals, are shown in Table 5 for six trials where data for individual daily yields per cow were available. Data for milk yields on the first day of each treatment regime were omitted as a transition between treatments. The number of animals in Table 5 was fewer than the number shown in Table 1 due to the removal of data during the filtering process (see section 2.6). The number of days in each period varied between trials due to differences in herbage mass and rate of daily herbage growth. Treatment differences in mean daily milk yields per animal were generally small, with higher yields for the 'Control' treatment than for the 'GrazeMore' treatment in 4 of the 6 trials, the difference of 1.9 litres/cow/day in Trial 11 being statistically significant. The numerical differences registered between the treatment mean yields in Trials 6 and 12 were not statistically significant.

Table 5. Mean corrected milk yield (litres/cow per day) and power analysis of achieved experimental designs (replicate days for each treatment) for assessing differences in milk yield of dairy cows submitted to two herbage allocation methods ('GrazeMore' and 'Control') in commercial farms (trials 3, 6, 11-14). A separate analysis was applied for each trial. The least significant difference (LSD) indicates the smallest differences that would have been statistically significant at the 5 % level.

Trial	N°. of animals	Average DIM at start[1]	Milk yield (litres/cow/day)						Power Calculations Overall	
			Control mean	GrazeMore mean	SED[2]	t-stat[3]	df[4]	t-prob[5]	LSD	df
3	95	239	23.2	22.1	0.530	1.99	8.82	0.079	1.221	8.82
6	79	273	27.2	28.3	0.679	-1.59	14	0.134	1.456	14
11	174	256	23.5	21.6	0.364	5.07	16	<0.001	0.771	16
12	166	210	26.8	27.6	0.376	-2.13	13.49	0.052	0.813	13.49
13	97	126	27.8	27.7	0.365	0.15	16	0.879	0.774	16
14	142	168	29.8	29.6	0.328	0.44	15	0.666	0.700	15

[1]DIM = days in milk; [2] SED = standard error of the difference; [3] t-stat = t-statistic; [4]df = degrees of freedom. [5] t-prob = probability of a more extreme t-statistic (two-sided test) from the appropriate t-distribution.

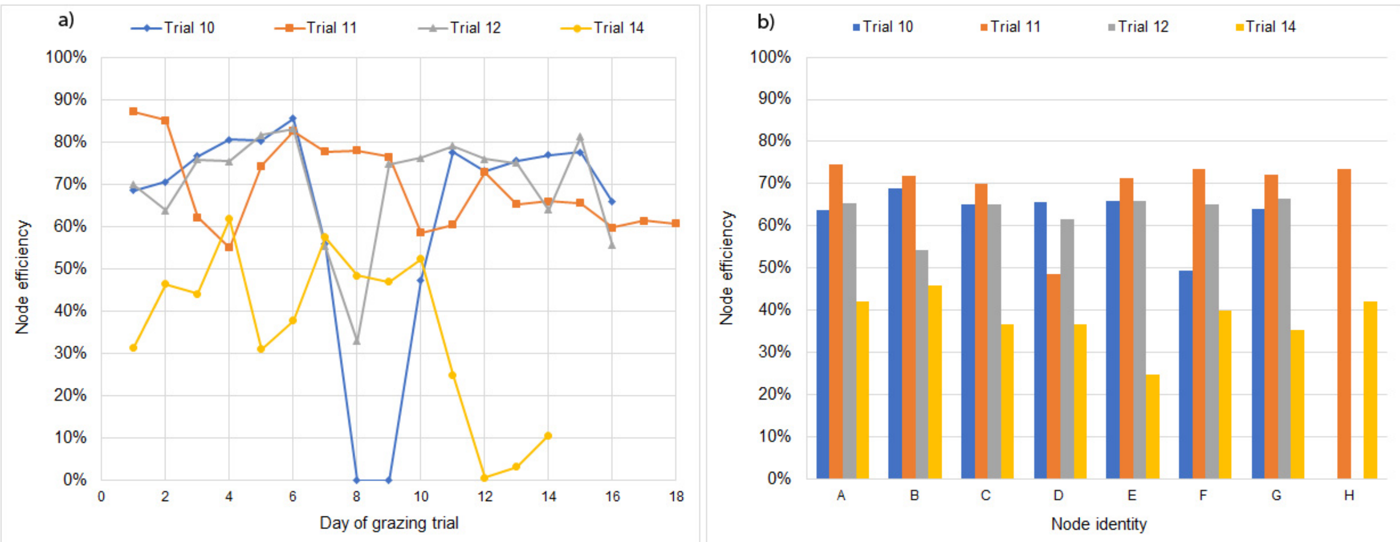

Figure 4. Node efficiency (percentage of data packets received): a) by node identity, and b) by day of trial, for each of Trials 10, 11, 12 and 14.

Table 4. Herbage intake and grazing efficiency (Trials 3, 5, 6, 9, 11-14) of dairy cows submitted to two herbage allocation methods ('GrazeMore' and 'Control') in commercial farms. Separate analyses were applied for each trial and grazing period. Day and Night analyses omit any back-grazing, 24 h analyses include back-grazing.

Trial	Grazing period	Number of days		Daily herbage intake (kg DM/cow)			SED[1]	t-stat[2]	df[3]	t-prob[4]	Grazing efficiency (%)5			SED	t-stat	df	t-prob
		Control	GrazeMore	Control mean	GrazeMore mean	Difference (GrazeMore-Control)					Control mean	GrazeMore mean	Difference (GrazeMore-Control)				
3	Day	8	9	9.27	5.89	-3.38	1.540	2.19	15	0.044	43.4	32.4	-11.1	4.23	2.62	15	0.019
5	Day	5	9	6.24	9.11	2.87	0.880	3.26	12	0.007	44.2	48.5	4.34	1.35	3.22	4.72	0.025
5	Night	5	8	6.51	7.69	1.18	1.002	1.18	11	0.264	45.9	47.2	1.32	2.54	0.52	7.49	0.617
5	24h	5	8	12.8	16.7	3.91	1.460	2.67	11	0.022	45.2	47.8	2.64	1.63	1.62	11	0.134
6	Day	11	6	2.54	6.72	4.18	0.620	6.74	15	<0.001	32.8	45.6	12.7	2.45	5.21	13.88	< 0.001
9	Day	9	6	7.93	8.34	4.08	0.999	0.41	12	0.690	36.7	26.0	-10.8	3.38	3.19	12	0.008
9	Night	9	6	8.61	6.97	-1.64	0.800	2.05	13	0.061	37.9	27.6	-10.2	4.25	2.41	6.14	0.052
9	24h	9	6	16.1	15.3	-0.81	1.300	0.63	12	0.542	26.6	21.3	-5.24	2.55	2.06	12	0.062
11	Day	7	11	8.97	8.09	-0.88	1.435	0.62	16	0.546	34.4	22.4	-12.0	3.55	3.37	7.09	0.012
11	Night	7	11	7.97	8.10	0.14	1.100	0.12	16	0.903	34.5	29.1	-5.39	3.87	1.39	16	0.183
11	24h	7	11	17.0	16.7	-0.34	2.320	0.15	16	0.886	30.7	20.6	-10.1	4.13	2.44	16	0.027
12	Day	11	8	6.35	9.10	2.75	0.691	3.98	14.71	0.001	44.3	45.5	1.19	3.62	0.33	17	0.747
12	Night	12	8	6.59	6.24	-0.35	0.798	0.44	18	0.662	47.6	43.4	-4.13	3.90	1.06	17	0.305
12	24h	12	8	12.5	15.6	3.09	1.210	2.56	18	0.020	42.3	40.2	-2.03	4.09	0.50	17	0.626
13	Day	11	8	4.75	6.64	1.89	0.690	2.74	17	0.014	33.5	29.1	-4.43	3.07	1.45	17	0.166
13	Night	12	8	5.75	4.86	-0.89	0.684	1.30	17	0.210	39.5	28.6	-10.9	3.39	3.23	18	0.005
13	24h	11	8	10.4	11.5	1.12	1.060	1.05	17	0.307	34.7	27.7	-6.99	3.19	2.19	18	0.043
14	Day	11	8	6.46	7.33	0.86	0.787	1.10	17	0.287	30.4	34.7	4.22	2.81	1.50	17	0.152
14	Night	11	8	2.13	7.05	4.92	1.139	4.32	17	< 0.001	9.79	38.0	28.2	5.24	5.39	13.16	< 0.001
14	24h	11	8	8.70	15.0	6.29	1.740	3.60	17	0.002	16.0	29.6	13.6	5.33	2.55	17	0.021

[1] SED = standard error of the difference
[2] t-stat = t-statistic
[3] df = degrees of freedom
[4] t-prob = probability of a more extreme t-statistic (two-sided test) from the appropriate t-distribution
[5] Efficiency = Intake as % of kg DM allowance/cow/day

Discussion

This paper presents results from 11 trials on eight commercial farms, acknowledging the influence of farm and trial variations on the outcome. While using commercial farms has limitations, conducting 11 trials in controlled facilities was impractical. However, the study aimed to demonstrate the innovation's applicability across diverse farm settings for potential commercial use.

Test of hypotheses 1 and 2

In grazing ruminants, the meal and ingestive behaviour patterns are circadian (Gregorini *et al*., 2012). As stressed by Gregorini *et al*., (2013) ruminants prefer to graze during daylight hours but may also graze for short periods during the night (5-15 % of daily grazing time). The main meals are concentrated around twilight hours, dawn, and dusk, with dusk being the most intense and prolonged. However, the grazing bout at dawn may have been curtailed by the morning milking rou-tine. In temperate climates, they typically have three to five major meals per day, but this can vary based on external factors like grazing management (Gregorini *et al*., 2013). In our case study, we observed a diurnal pattern with three main grazing bouts during the day. The evening grazing bout was the biggest and on one farm trial it was split into two smaller bouts (Trials 11 and 12, herd G). Generally, there was minimal grazing activity occurring overnight. The more intense grazing events, indicated by a larger area below the pGraze curve, were typically observed in the late af-ternoon and evening. The methodology employed successfully triggered gate opening after the end of the morning grazing bout and created new grazing bouts in trials 11 and 12 and increased the size of the bout in trial 10. It had no effect in trial 14 possibly due to limited grass growth in the first part of the trial. However, evening grazing activity was reduced under the 'GrazeMore' treat-ment, limiting the impact across the 24 h period.

With regard to the second hypothesis, i.e., the effect of synchronised allocation of additional herbage on relevant variables, our findings were inconsistent in magnitude and direction between trials. Regarding herbage intake over a 24 h period, four trials showed greater values for 'GrazeMore', whereas 'Control' showed greater herbage intake in one trial. For two of the three trials where no differences were found between allocation methods, the apparent herbage intake associated with the increased allocation of herbage during the day was balanced by reductions in intake during the subsequent night period. This would suggest that in some grazing situations there is a limit to the total time cows are able to allocate to the act of grazing (Kilgour, 2012), i.e., grazing time is limited by the time requirements to ruminate and idle (i.e., non-grazing and non-ruminating activity) (Chilibroste *et al*., 2015). Interestingly, for the three trials (out of four) with the greatest differences in herbage intake in favour of 'GrazeMore', this increased intake during the day was not balanced by reduced intake at night. This would suggest that even though there is a time limitation for grazing (Kilgour, 2012), the grazing activity could have been more intense during the 'GrazeMore' stage, possibly involving a higher biting rate or larger bite sizes.

It was expected that a higher herbage DM intake would lead to higher milk yields. However, dif-ferences in milk yield between treatments were generally small and not statistically significant. Overall, three of the six trials with sufficient milk yield data showed changes of interest ($p < 0.10$). However, two trials showed that the 'GrazeMore' treatment slightly reduced milk yields and only one showed an increase. This lack of consistent response could be due to the relatively advanced stage of lactation of cows in some trials, who might be diverted a proportion of the additional energy consumed to recover body condition instead (Moran, 2005). For instance, in Trial 12, an increase in 24h herbage intake of 3.1 kg DM/day for the 'GrazeMore' treatment was reflected in a positive milk yield response of 0.8 litres/cow per day; however, similar responses to the 'GrazeMore' treatment were not seen in Trial 13, which comprised another group of cows on the same farm at the same time of year. These inconsistent results could be also explained by the differences in individual levels in herbage intake of the cows, since cattle show considerable group synchronicity in the initiation of grazing activity, although slightly less so in terminating this activity (Chilibroste *et al*., 2015), highlighting the complexity of factors driving the ingestive behaviour of dairy cows. During the trials it was evident that although cows ate more herbage after the initial 'GrazeMore' allocation, they possibly compensated by grazing less during the following evening period. Possibly, the timing of additional pasture allocation influenced the response (Abrahamse *et al*., 2009) and introduction of additional pasture later in the day might have been more beneficial. In order to reduce the impact of confounding effects, the milk yield data was corrected for DIM (i.e., to compare all the cows as if they were in 150 DIM), and the amount of in-parlour feeding was held constant through each trial, but it would seem that there are other factors such as changes in weather, pasture age, botanical species content, pregrazing herbage mass, cow type and management that have affected the milk yields. However, since three trials were in the same geographical location, two of which were over the same time period, assessment of environmental factors influencing the response would have been unlikely to reveal significant effects.

Another factor that could have affected the results is the method used for estimation of herbage intake (i.e., rising platemeter). This indirect technique is reliable over a short time scale (e.g., 24h) (Smith *et al*., 2021). The rising platemeter technique is useful for obtaining herd estimates of pasture intake for management decisions and for the determination of pasture parameters asso-ciated with intake (Reeves *et al*., 1996). The accuracy of the estimations would increase with a prediction equation developed for each farm (Lukuyu *et al*., 2014), and for pre-grazing and postgrazing herbage (Reeves *et al*., 1996), though this task was beyond the objective of this case study. Macoon *et al*., (2003) states that, when appropriate for the research objectives, herbage disappearance method may be useful and less costly alternatives to using the pulse-dose method. Another disappearance method such as the classical sward cutting method can give a good estimate of herbage intake by grazing animals, but often a large variation in the estimation of herbage mass is found. Variation of both pre and post-grazing measurements are added; hence, the herbage intake values become even more variable (Smit *et al*., 2005), which was likely the case for the present study. Consequently, the total 24-hour grazing efficiency values were not particularly reliable for some trials because these figures included the impact of back-grazing, where, often, the estimate of herbage intake done with the raising plate meter was close to zero, but a relatively substantial area of herbage was available which magnified any errors in estimated feed intake. However, separate day and night analyses were not impacted by these back-grazing assessments.

The statistical power of the design to test the ‘GrazeMore’ hypothesis with regard to milk yield (hypothesis 2) was assessed by considering the size of the least significant difference (LSD, at the 5 % significance level) for each trial, obtained from the information about day-to-day variation in responses having allowed for any differences in the mean yields for the two treatments. In all cases, a milk yield difference of 2 litres/animal/day would have been statistically highly significant should such a difference have been observed.

Main Practical Limitations

This paper reports results from 14 trials across 8 commercial farms. The variability in the results will have been influenced by differences between farms and between trials that we could not control. This is a disadvantage of using commercial farms but the costs and resources to run one trial on an experimental facility were beyond this project and to run 14 such trials is probably not possible in any country. This issue was anticipated at the start of the project, but it was felt that if this innovation was to be of commercial interest to the industry it would have to work and show benefits across a range of farms and environments under commercial conditions.

The initial experimental design was to identify suitable pairs of farms (within 20 miles of each other) where, at least, some cow groups were grazed without buffer feeding, that used a rising plate meter and the AgriNet system (Irish Farm Computers Ltd., Ireland) and recorded daily milk yields through the parlour. Farms were to be identified in pairs that were near each other so that two farms could be enrolled in each trial and the treatment/control periods reversed between the two farms. However, it was only possible to identify a few farms that fit the selection criteria, and it was not possible to work with pairs of farms simultaneously. In addition, trial farms were identified several months in advance of the actual trial; however, at the time of running the trial, various factors had changed that impacted the running of and results from some of the trials. A further issue was that the farms needed to have surplus grass at the time of trial to enable the additional herbage allowance to be provided during the GrazeMore treatment period. Unfortunately, droughts and heatwaves limited grass growth. For instance, trial 7 was in mid-summer on a farm on well-draining chalk-based soils and hence suffered very poor grass growth in the dry summer such that the farm management would not allow an additional allocation of pasture. In Trial 10, grass covers had been managed to be very high and outside the predictive range of the rising plate meter. Additionally, heterogeneous sward structures developed through the grazing season and back-grazing made it difficult to as-sess forage mass and allocate grazing areas accurately (Merino *et al*., 2018). Overall, data was incomplete due to poor grazing infrastructures in Trials 1 and 2 and low grass availability restricting the length of grazing periods in Trials 1 to 8 and also in Trial 10. Although the experimental design could not be fully implemented on these farms, the trials were still very valuable for developing the data capture and processing aspects and refining the cloud-based algorithms.

The Covid-19 pandemic severely restricted field work due to lockdown measures in 2020 and 2021 that prevented access to farms by the research team, and several potential trials were lost. In the early stages of the project, we were unable to fabricate LoRaWAN nodes due to severe global component shortages. Early trials (Trials 1 to 4) were therefore carried out using inferior generic Chinese LoRaWAN nodes. These nodes had performance issues related to transmission, and poor battery management firmware limited battery lives to only 2 to 3 weeks. In later trials, we were able to revert to fabricating our nodes, which gave better performance and battery life (6-8 months). Lo-RaWAN signal transmission is limited by line of sight. In several trials, woodlands and ancillary buildings limited signal transmission, and on farm H, the hilly topography of the farm made some fields inaccessible to LoRaWAN signals. Secondary LoRaWAN gateways can be used to cover 'dead spots', but the logistics of identifying areas requiring additional gateways, supplying mains electricity or large solar panels and the associated security required made this impractical for a short-term trial.

Conclusions

In conclusion, the variable and inconsistent responses to the 'GrazeMore' treatment indicate that the concept of allocating additional areas of pasture automatically at specific times requires further development. In these trials it was possible to change the pattern of feeding, but in the current format, it was not possible to consistently increase grazing intakes and milk yields. However, the timing of additional daily pasture allocation may be critical in determining the extent to which dairy cows are likely to respond in terms of increased herbage intake and subsequent milk yield. For example, additional pasture allocation in the early evening, coincidental with the main grazing period, may be worthy of investigation. The LoRaWAN system performed well in the farm envi-ronment when using our node design, but additional LoRa gateways may be necessary to cope with hilly terrains especially when sending data from the gateway to the gate-actuator node in the grazing paddocks.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Data Availability: Data are available from Rothamsted Research (Chamberlain *et al*., 2022a, 2022b, 2022c, 2022d)

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